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INTERPRETATION OF THE PROMINENCE DIFFERENTIAL EMISSION MEASURE FOR THREE GEOMETRIES

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ABSTRACT

We have used prominence EUV line intensities observed from Skylab to derive the differential emission measure Q(T) in the prominence-corona (PC) interface from 3×10^4 to 3×10^6 K, including the effects of Lyman Continuum absorption. Using lines both shortward and longward of the Lyman limit, we have estimated the importance of absorption as a function of temperature. The magnitude of the absorption, as well as its rate of increase as a function of temperature, place limits on the thread scales and the character of the interfilar medium. We have calculated models based on three assumed geometries: 1) Threads with hot sheaths and cool cores; 2) Isothermal threads; 3) Threads with longitudinal temperature gradients along the magnetic field. Comparison of the absorption computed from these models with the observed absorption in prominences shows that none of the geometries is totally satisfactory.

1.0 INTRODUCTION

Prominences have been observed in emission in EUV lines formed at temperatures between 10^4 and 10^6 K from the OSO-6 spacecraft (Noyes et al 1972) and rocket flights (Jones, Parkinson, Speer and Yang 1971; Orrall and Speer 1974, Yang et al 1975), Skylab (Schmahl et al 1974, Schmahl and Hildner 1977, Moe et al 1979, Mariska, Doschek and Feldman 1979, Feldman and Doschek 1977), OSO-8 (Bonnet et al 1978; Vial et al 1979, 1981) and Solar Max (Poland and Tandberg-Hanssen 1983). Orrall and Speer (1974) attributed the EUV emission to the prominence-corona interface, henceforth called the PC interface. Orrall and Schmahl (1976 Paper I) showed that the PC interface was similar to, but significantly different than, the chromosphere-corona transition region. This study showed that lines longward of the Lyman limit were more intense than those lines of similar formation temperature which lay shortward of the Lyman limit. Estimates of the amount of absorbing hydrogen in prominences were made in Paper I, but a subsequent analysis of the absolute intensities in prominences and the solar disk (Schmahl and Orrall 1979, Paper II) showed that the Lyman Continuum (LC) absorption had been underestimated. The absolute intensities of EUV lines can, in principle, provide well-determined models of density as a function of temperature in prominences, as has been done for the quiet and active disk (Withbroe 1976, 1977; Raymond and Doyle 1981). In this paper, we tabulate the intensities of EUV emission lines for a well-observed prominence, and compute the differential emission measure Q(T) = $N_e^2 d\ell/dT$ including the effects of absorption, for two different thread geometries, and a class of magnetic orientations. We conclude with a discussion of the fit of the different model geometries to the data and other discriminating tests that could be made of the models.

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2.0 DIFFERENTIAL EMISSION MEASURES

The line set for the prominences of Paper I was compared with the spectral data of Vernazza and Reeves (1978) and Noyes et al (1985) obtained for disk and coronal (non-prominence) pointings. Blends or spurious lines were deleted. The line intensities were determined using the calibration published by Reeves et al (1977).

A number of authors have computed differential emission measures of solar features (Withbroe 1977, Raymond and Doyle 1981; Noyes et al. 1985). In general one determines a function Q(T) such that the intensities of a set of m lines approximately satisfy the relation:

$$I_\lambda^{(k)} = c_k \int Q(T)\, G_k(T)\, dT, \qquad k = 1 \text{ to } m,$$

where $c_k = 1.74 \times 10^{-16} A_k g_{eff} f_{12}^{(k)}$, and the symbols have their usual meaning (cf Withbroe 1976).

We have obtained a least square fit Q(T) to this equation for the prominence of 12 January 1974 (Figure 1). The two curves (1) and (2) for Q(T) in Figure 1 ($Q_o(T)$ and $Q_{abs}(T)$, respectively), are for wavelengths longward and shortward of the Lyman limit. There is a considerable difference between the curves. and it is seen that the ratio Q_{abs}/Q_o increases from about 1/16 at log T = 5.0 to about 1/3 at log T = 6.2. This variation with temperature for the attenuation of lines by the Lyman continuum was noted in Paper I, but in a somewhat less quantitative way. We have included the changes in rate coefficients suggested by Doschek and Feldman (1982) and the changes (from Paper I) are denoted by arrows in the Figure.

In papers I and II, there were no coronal lines whose wavelengths were longward of the Lyman limit, and it was difficult to estimate the effect of absorption for formation temperatures above 10^6 K. We have therefore included the Fe XII λ1242.2 line, using the emissivity computed by Flower (1977). (Feldman, Cohen and Doschek 1983 have confirmed his analysis). This provides information about Q(T) for T = $10^{6.2}$. For higher temperatures, we have incorporated the X-ray upper limit ($Q < 6.2 \times 10^{19}$ cm^{-5} k^{-1}) reported by Serio et al (1978).

3. GENERAL CONSIDERATIONS

One of our objectives for determining the differential emission measure Q(T) is to give information about the fine structure of prominences. It is clear, however, that there is no unique way in which the distributions of density $N_e(\ell)$ and temperature $T_e(\ell)$ as a function of path length (ℓ) may be unfolded from the function Q(T). We must, instead, depend on more specific geometric models relating the temperature structure to the thread structure. The two main geometries proposed are: 1) Threads with cool cores and hot sheaths (Orrall and Speer, 1974, Yang, Nicholls and Morgan 1975, Orrall and Schmahl 1980), 2) Isothermal threads of various temperatures (Poland and Tandberg-Hanssen 1984). 3) Magnetically aligned threads with temperature and density varying only along the axis of the thread (e.g. Mariska 1985), or threads with lines of force not aligned (Low, 1982, Athay et al 1983, Leroy et al 1984).

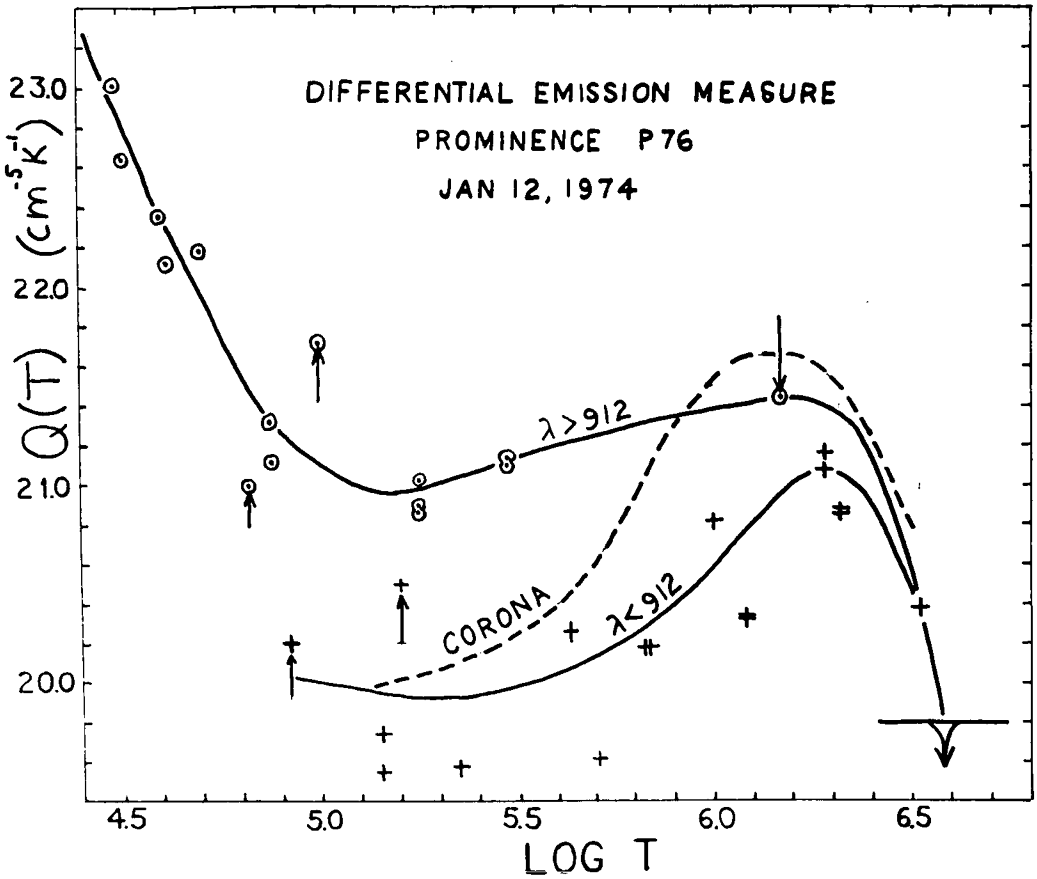

Figure 1. Emission measure data for 29 spectral lines in a limb prominence observed with the HCO spectroheliometer on SKYLAB. The bottom curve shows the differential emission measure function $Q_{abs}(T)$ fitted to lines with wavelengths < 912Å. The top curve shows $Q_0(T)$ computed using only lines with wavelengths > 912Å, including the emission of the ambient corona along the line of sight. The middle curve shows Q(T) after deleting the estimated contribution not associated with the prominence. The dashed curve shows $Q_{cor}(T)$ for off-limb spectra (Vernazza and Reeves 1978).

4. APPLICATION OF GEOMETRIES TO Q(T)

Previous attempts to model threads have either used single slabs or regular arrays of cylinders. It seems more appropriate, however, to incorporate some degree of randomness in the arrays of threads, and this does not add any significant complexity to the problem. Our calculations apply mainly to average spectra or to spectra obtained with a wide slit which encompasses many structures. For the above geometries we shall take the threads to be cylinders parallel to the z axis, distributed randomly with uniform probability between the y = 0 plane and the y = L plane. The radius r_i of the i^{th} thread is assumed to be << L, and its (random) position (x_i, y_i) is assumed to follow a rectangular probability distribution between y = 0 and y = L, and x = 0, and x = L. Thus we may compute the expectation value of the number of intersections, ⟨m(r)⟩, the expectation

optical depth, $\langle\tau\rangle$, and the expectation differential emission measure $\langle Q_o(T)\rangle$ with $\langle\tau\rangle = 0$, and $\langle Q_{abs}(T)\rangle$ with $\langle\tau\rangle \neq 0$. (For reasons of space, we cannot present these calculations. The details will be published elsewhere.)

4.1 GEOMETRY #1: COOL CORES/HOT SHEATHS

For the core/sheath geometry we have calculated the variation with temperature of the "absorption factor" $Q_{abs}(T)/Q_o(T)$. Figure 2 shows curves for a few values of the parameters: the total expectation optical depth, b (the pressure index, where $p \propto T^{b-1}$), r_o (thread core radius) and N_o (the electron density at T = 20000 K). In general, the absorption factor rises as a function of T, and shows the greatest difference between its low and high temperature values when τ(total) is large.

It appears that core/sheath thread models (Geometry #1) can explain the observed variation of absorption as a function of temperature only if $b > 1.5$, which requires a large rate of increase in pressure through the PC interface.

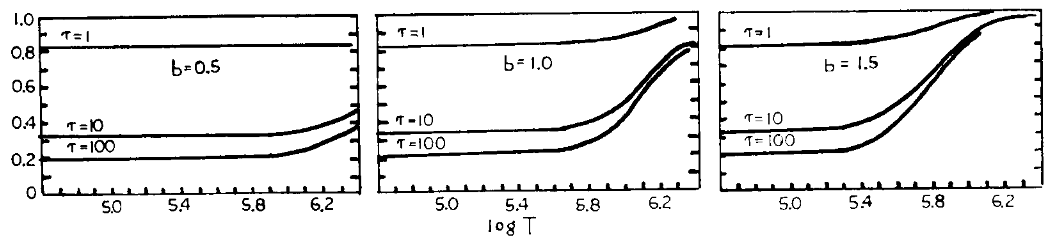

Figure 2. Computed curves of $Q_{abs}(T)/Q_o(T)$ for Geometry #1. The density, thread radius and expectation number of threads in the line of sight are the same in all three cases, while the parameter b in $N_e(T) = AT^b$ is varied: b = 0, 1, 1.5. It appears that $b > 1.5$ in order to get a variation similar to that observed (Figure 1).

4.2 GEOMETRY #2: ISOTHERMAL THREADS

The geometry suggested by Poland and Tandberg-Hanssen (1983) is one for which hot material appears displaced from cool material at distances greater than the thread radius. Thus we may model this as a set of isothermal threads of various temperatures with random positions uncorrelated in the x and y directions. Again we compute the expectation value of the emission measure from a random thread in the presence of cylindrical absorbing threads, each of optical depth τ_1 along a diameter ($2r_o$). The calculations yield: $\langle Q_{abs}(\tau)\rangle = \langle Q(0)\rangle\,(1-\exp(-\pi m\tau_1))/\pi m\tau_1$. The expectation absorption factor, a decreasing function of $m\tau_1$, is equivalent to that of a slab with uniform emissivity and absorptivity, having optical depth $\tau(\mathrm{tot}) = \pi m\tau_1$ (the expectation optical depth.). In this geometry there is no explicit dependence of the absorption factor on temperature through a radial dependence T(r), but instead the dependence is obtained by choosing m (the expectation number of threads) to be a function of T such that the computed and observed Q(T) agree.

As previously, we assumed a density dependence of the form T^b. Then given m(T) threads of temperature T, there must be $m'(T)dT$ threads in the range T, T+dT. Thus the emission measure distribution must satisfy: $Q(T)dT = N_o^2(T/T_o)^{2b}\,\pi r\, m'(T)dT$. We may as well assume that the threads are of the same diameter $r_o = R$, although variable r(T) could be included in the same way as density ($N_e = N_o(T/T_e)^b$).

Integrating the expression for $m'(T)$ gives:

$$m(T) = m_o + \int_{T_o}^{T} \frac{Q(T)\, dT}{N_o^2\, \pi\, R(T/T_o)^b} .$$

Clearly m is an increasing function of T, but the absorption factor Q_{abs}/Q_o is a decreasing function of m. Hence no combination of parameters in this geometry will make the absorption factor increase as a function of temperature.

4.3 GEOMETRY #3: MAGNETIC FIELD PARALLEL GRAD T

A number of possibilities and problems become apparent if the temperature gradient in prominences is parallel to the magnetic field, (which may, or may not, be parallel to the axis of the threads). The most interesting consequence of this is that the emission from the PC interface may result mainly from the energy input by thermal conduction from the corona. In this case, the observed function Q(T) must be derivable from the energy balance, and $Q_o(T)$ in Figure 1 provides a test for such a model.

The basic problems of energy balance in prominences have been summarized by Tandberg-Hanssen (1974) and others. We restrict ourselves to the case in which the radiative flux is balanced by the conductive flux from the corona. This case has been analyzed by Rosner et al (1978) for active region loops, and the same mathematical method may be applied to this prominence geometry. We assume that mechanical heating is restricted to the coronal domain $T > T_c$ where T_c is approximately 10^6 K. Then the balance of conductive and radiative flux may be expressed as: $T/Q(T)^2 = (8k^2/Kp^2) \int dT'\, T'^{-1/2}\, P(T')$.

There is essentially only one free parameter which may be varied to match the computed Q(T) with the one derived directly from observations: the coronal pressure N_oT_o. For any value of the pressure, the function Q(T) is very flat. In fact, regardless of the (positive) radiative loss function assumed, Q(T) may not rise faster than $T^{1/2}$. At a temperature of 10^5 K, a reasonable fit to the observed Q(T) is given if $\log(N_oT_o) = 14.2$. At higher temperatures, the Q(T) derived from the conductive balance is reasonably close to curve 1 in Figure 1.

In the temperature domain log T = 5.0 to 6.0, Q(T) varies roughly as a power law with index a = 0.2 (± 0.2). Assuming constant pressure and integrating Q(T), the distance s expressed as a function of temperature is:
$s = s_o + 10^{15} T_5^{3+a}\, Q(T_o)/N_oT_o(3+a)$.

In our case, the ratio $Q(T)/N_oT_o$ is approximately 1×10^{-8}. Thus the distance of the 5×10^5 K level from the 1×10^5 K level will be approximately 5" (the size of the Harvard slit). It has been shown that prominences start becoming more diffuse (at the 5" scale) at temperatures around 5×10^5 K (Paper I and Schmahl 1979). Thus if the PC interface wraps around (or curves into) the cool cores of threads, (assuming they are less than or of order 0.5" in diameter) then the radius must exceed 5" above half a million degrees. At higher temperatures, the radius would be greater still, and thus the hotter portions of the interface would be more exposed to view and less subject to absorption, much like Geometry #1. One would expect the ratio Q_{abs}/Q_o to be an increasing function of temperature, but the rate of increase would depend strongly on the smallest geometrical scales, which are largely unknown.

5. DISCUSSION AND CONCLUSIONS

Both of the two thread geometries studied herein have certain shortcomings or difficulties, particularly with regard to the Lyman continuum absorption, and its apparent decrease at higher temperatures. Geometry #1, where cool threads are surrounded by hot sheaths, was advanced to explain the facts that emission appears thread-like and co-spatial (to 5") in lines formed at many temperatures. This geometry is not easily explained in terms of an energy budget, but it can explain the apparent decrease of absorption with temperature if the pressure is an increasing function of radius. However, the pressure must increase by at least two orders of magnitude (b = 1) in the range $10^5 < T < 10^6$ K and this seems rather improbable.

Geometry #2 (isothermal threads) has been invoked to explain the appearance of filamentary emission with little axial variation, but apparently uncorrelated (or variable) line emission from thread to thread. Because of the assumed lack of spatial correlation between temperature regimes, this geometry cannot explain the observed decrease of absorption as a function of temperature.

Geometry #3 (grad T $||\vec{B}$) has the virtue that radiation losses (at least for $2 \times 10^4 < T < 10^6$ K) can be balanced by conductive flux from the corona. This geometry can be combined with geometry #1, as in Low's (1982) model. The classical absorption (LTE) mechanism, however, cannot readily explain the observed amount of absorption, unless there are multiple threads or sheets along the line of sight (see geometry #1 and Paper II). On the other hand, the radiative-conductive flux balance cannot be maintained if there are multiple enfilades (sheets) of threads hanging on the same magnetic field lines, since the conductive flux will be used up by the outermost sheets.

The non-LTE mechanism proposed by Shoub (1983) might explain the existence and variation of absorption. However, it should be noted that there seems to be little positive evidence in terms of line widths (Feldman and Doschek 1977) or temperature diagnostics (Doyle et al 1985), that hot emission occurs in cool media, as required by Shoub. Further, in the absence of a simple analytic approximation for Shoub's mechanism, we are unable to estimate its importance for different thread geometries in prominences.

The observations of more EUV lines with better statistics, more pressure and density diagnostics, particularly at high temperatures, combined with improved resolution at wavelengths spanning the Lyman limit, may be required to decide the final issue of the appropriate geometry for the PC interface.

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